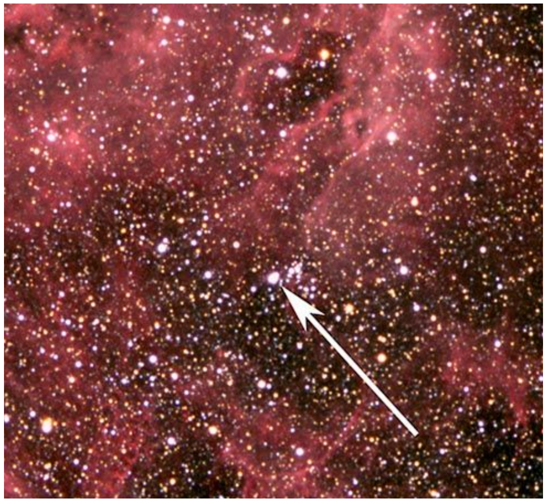
Observing the diffuse supernova neutrino background



SN 1987A, Anglo-Australian Observatory/David Malin Images

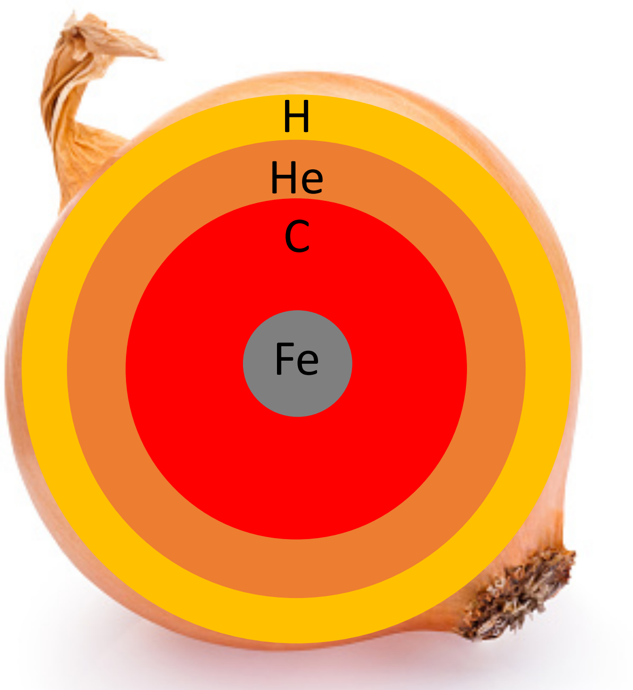
Peter Madigan

Outline

What is the diffuse supernova neutrino background (DSNB)?
Why search for the DSNB?

Recent DSNB searches
Future of the DSNB

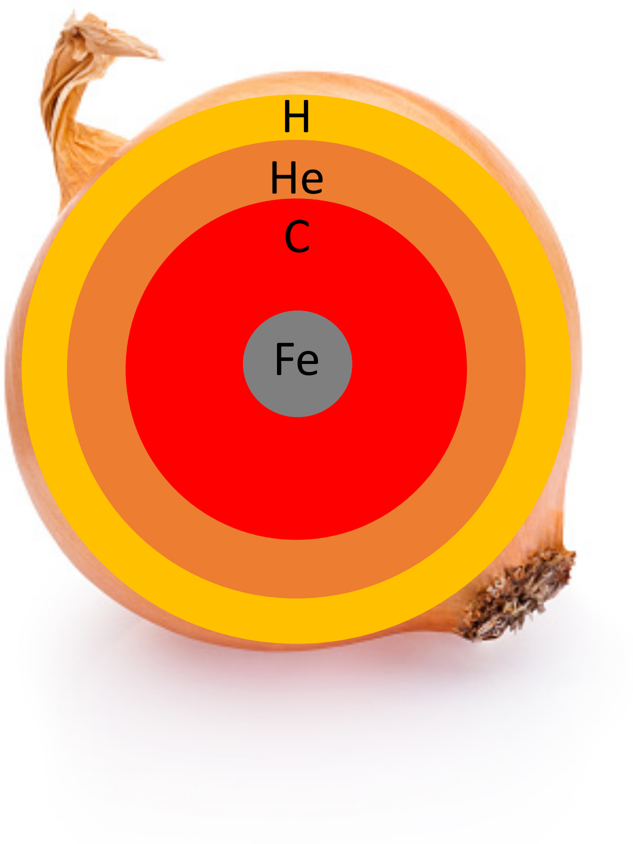
The lifecycle of a star



Stars fuse light nuclei into heavier and heavier nuclei.
Requiring hotter temperatures to fuse.

Iron ends the fusion cycle.

The lifecycle of a star



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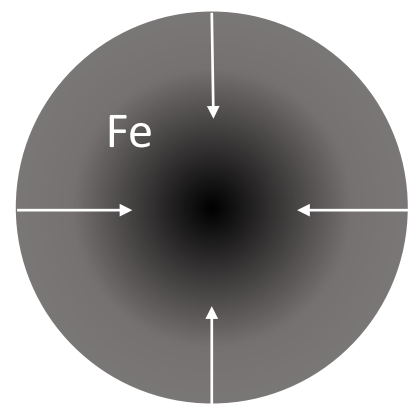

The inward gravitational pressure of the core eventually overcomes the outward thermal/e-degeneracy pressure. (>8M)

Collapsing the core into neutron star.

Neutrino emission

During collapse,

$$\left.\begin{aligned} p + e^- &\rightarrow n + \nu_e \\ n &\rightarrow n + \nu + \bar{\nu} \end{aligned}\right\} \text{99\% of energy released (~0.2 solar masses)}$$

Core is on the order of nuclear densities so the neutrino scattering length is appreciable:

Most of the energy is released through neutrinos.

Neutrinos are likely emitted with a thermal spectrum.

$$\phi(E_\nu) = E_{\bar{\nu}_e,tot} \frac{120}{7\pi^4} \frac{E_\nu^2}{T^4} \frac{1}{e^{E_\nu/T} + 1}$$

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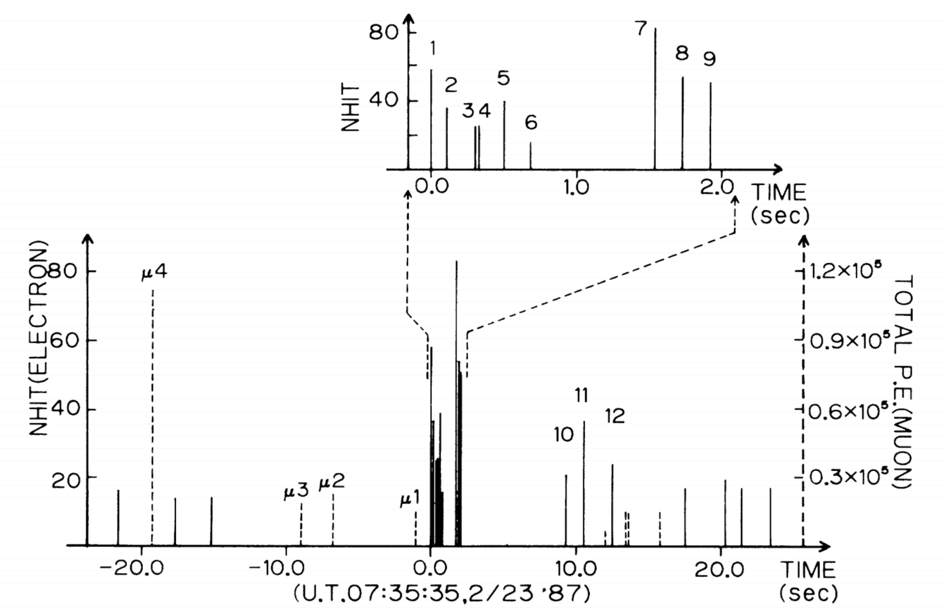
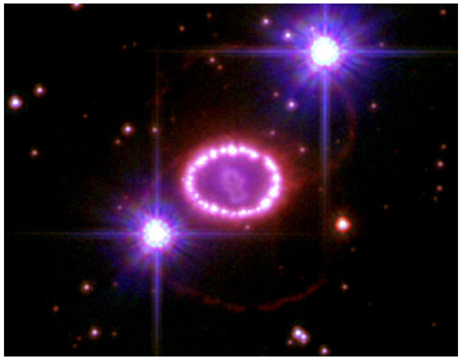
But how likely are we to see one of these?

Supernova rate

Not *that* likely… about 1 supernova within the Milky Way every 20-50 years.
Last one in 1987:



K. Hirata *et al.*, "Observation of a neutrino burst from the supernova SN1987A," *Phys. Rev. Lett.*, vol. 58, no. 14, pp. 1490–1493, Apr. 1987.



SN 1987A, NASA 2007.

So do we just hope for another one in our lifetime?

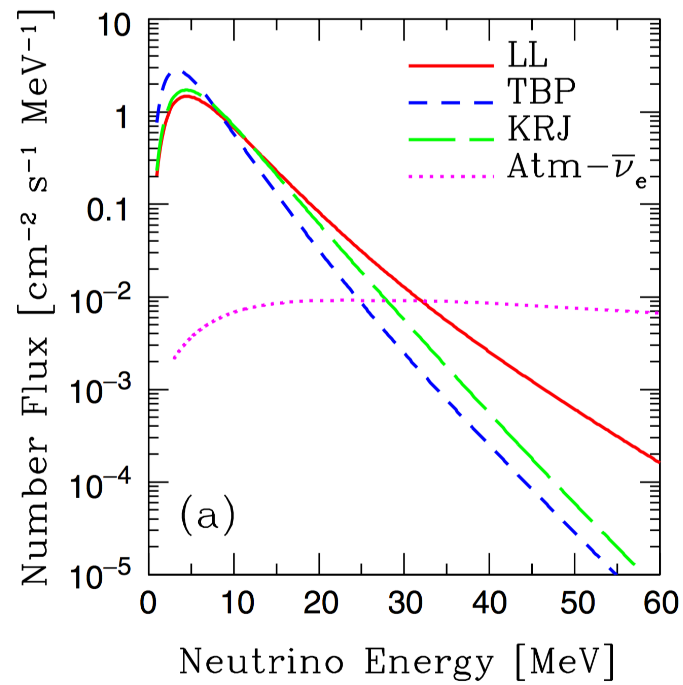
"Space is big. Really big. You just won't believe how vastly, hugely, mind-bogglingly big it is. I mean, you may think it's a long way down the road to the chemist, but that's just peanuts to space."

-Douglas Adams

At any given moment, there should be *some* neutrinos reaching Earth from some distant supernova.

A number density using the supernova rate as a function of redshift:

$$\frac{dn_\nu}{dE_\nu} = \int R_{SN}(z)(1+z)\phi(E'_\nu)\frac{dt}{dz}dz$$



S. Ando and K. Sato, "Relic neutrino background from cosmological supernovae," *New Journal of Physics*, vol. 6, pp. 170–170, Nov. 2004.

Why look for diffuse supernova neutrinos?

For astrophysics:

- DSNB measurements could be used to find star-formation rates and supernova rates, unaffected by interstellar dust.
- SN come directly from the core of the collapsing star and are the most sensitive probe of the physics that occurs in this process.

For particle physics:

- Flavor make-up of the DSNB is sensitive to the neutrino mass hierarchy and mixing angles.
- The long-baseline of the DSNB is sensitive to neutrino decay, which would have broad implications in particle physics and in astrophysics.

Looking for the DSNB:

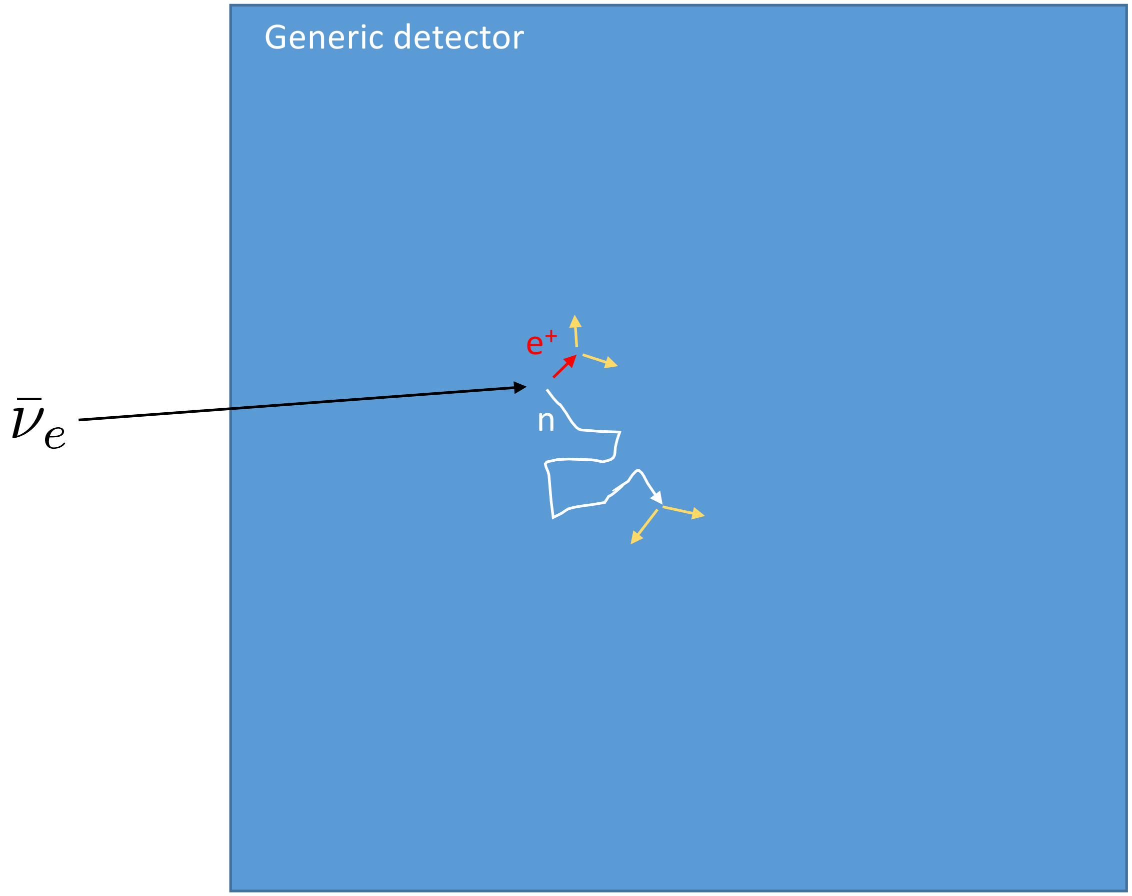
Roughly equal portions of all neutrino flavors.
Thermal spectrum peaked at about 4-8 MeV.
Isotropic.
Flux comparable to low-energy atmospheric neutrinos.

Low energy excludes CC interactions for muon and tau neutrinos.
Cross-sections make NC/elastic scattering unlikely.

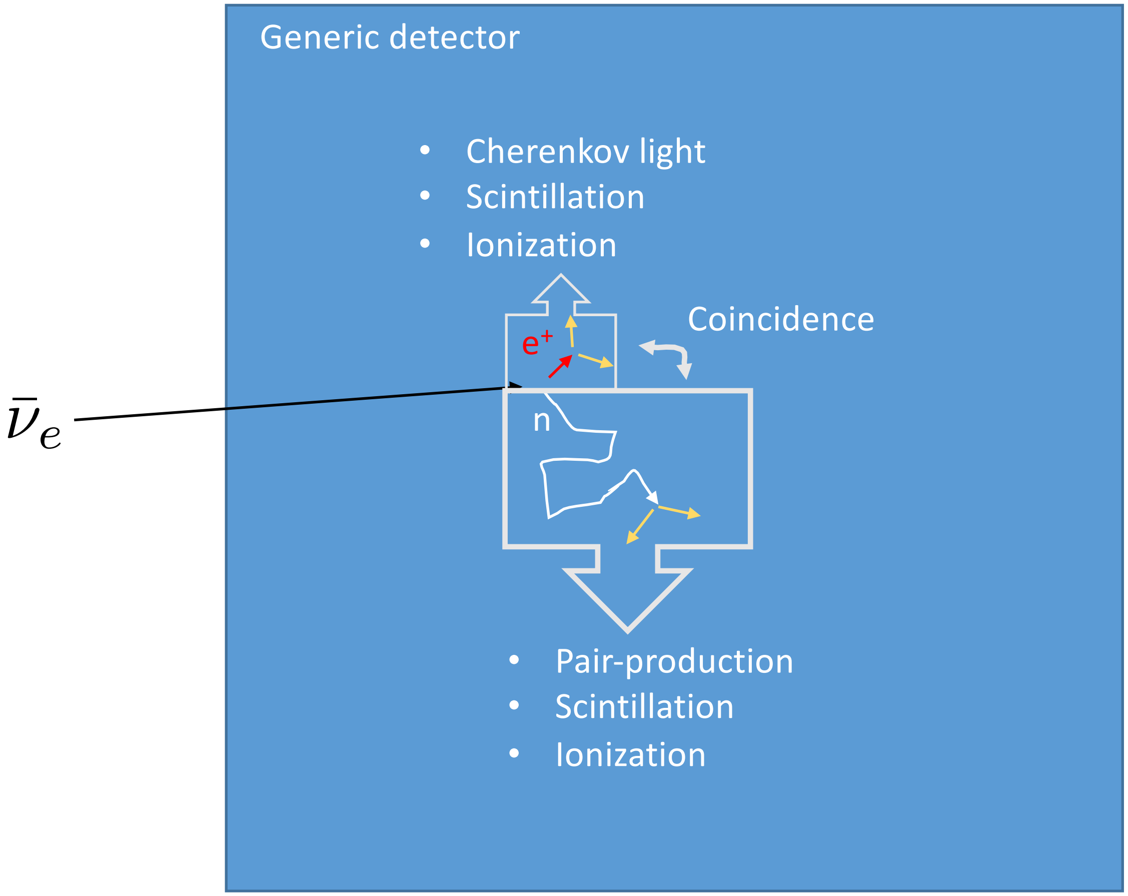
Observation will likely be made through an inverse beta decay search.

$$\bar{\nu}_e + p \rightarrow e^+ + n$$

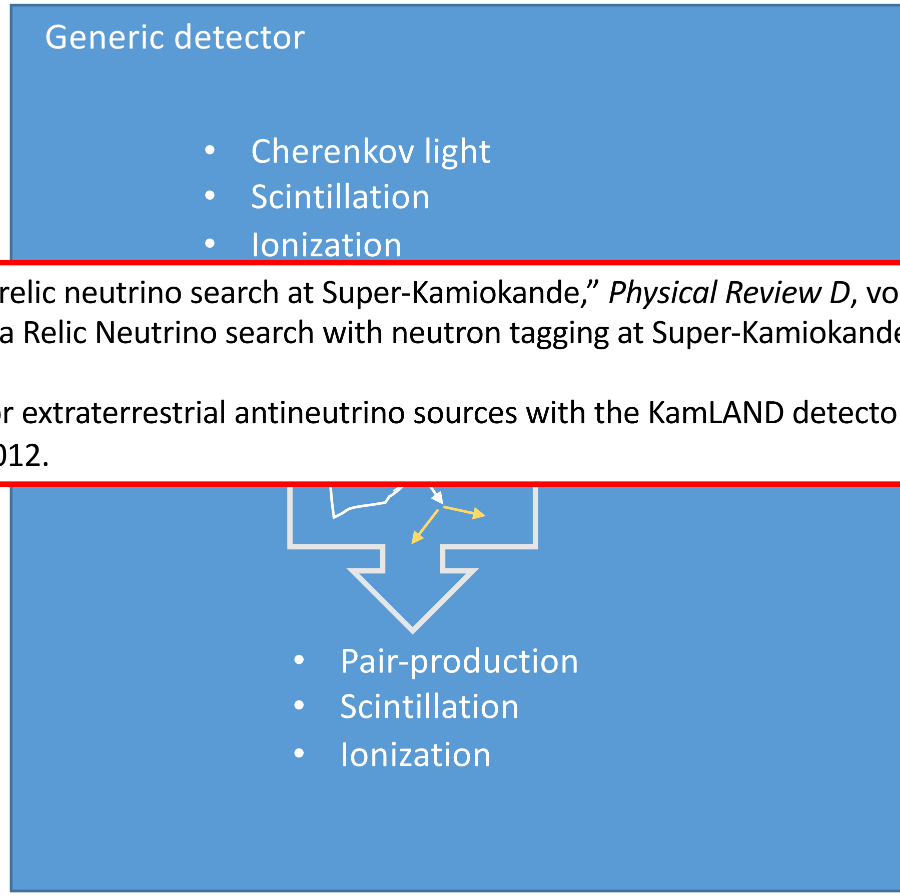
Signal



Signal


Generic detector
• Cherenkov light
• Scintillation
• Ionization
Coincidence
e^+
n
$\bar{\nu}_e$
• Pair-production
• Scintillation
• Ionization

Signal



[1] K. Bays *et al.*, “Supernova relic neutrino search at Super-Kamiokande,” *Physical Review D*, vol. 85, no. 5, Mar. 2012.
[2] H. Zhang *et al.*, “Supernova Relic Neutrino search with neutron tagging at Super-Kamiokande-IV,” *Astroparticle Physics*, vol. 60, pp. 41–46, Jan. 2015.
[3] A. Gando *et al.*, “Search for extraterrestrial antineutrino sources with the KamLAND detector,” *The Astrophysical Journal*, vol. 745, no. 2, p. 193, Feb. 2012.

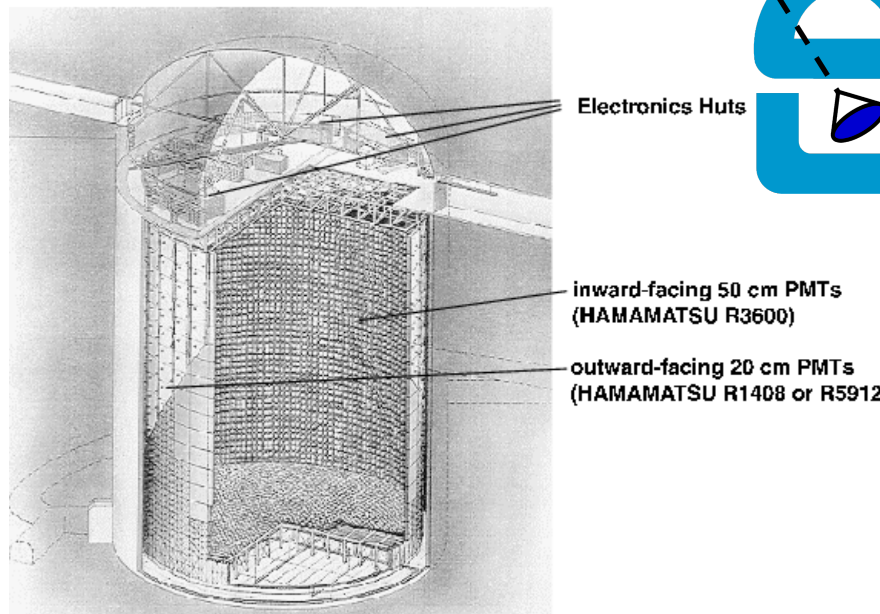
Super-Kamiokande

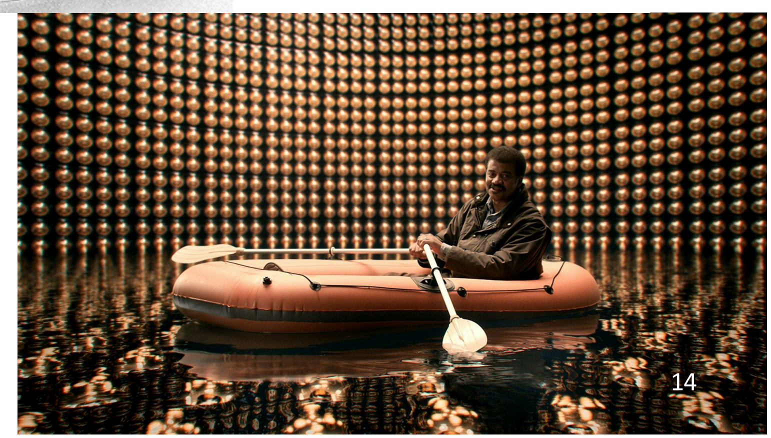
50kt water Cherenkov detector buried 1000m underground in the Kamioka mine (Japan).
Operating since 1996, published bounds on the DSNB in 2003, 2012, 2015, using two different methods:

- Only positron events
- Positron with neutron tagging

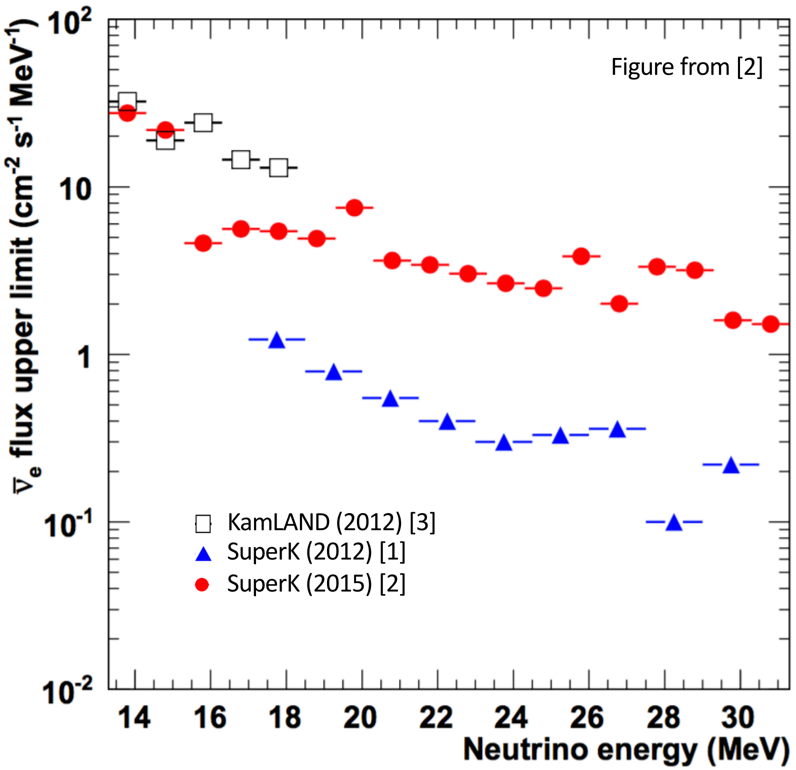
Biggest backgrounds:

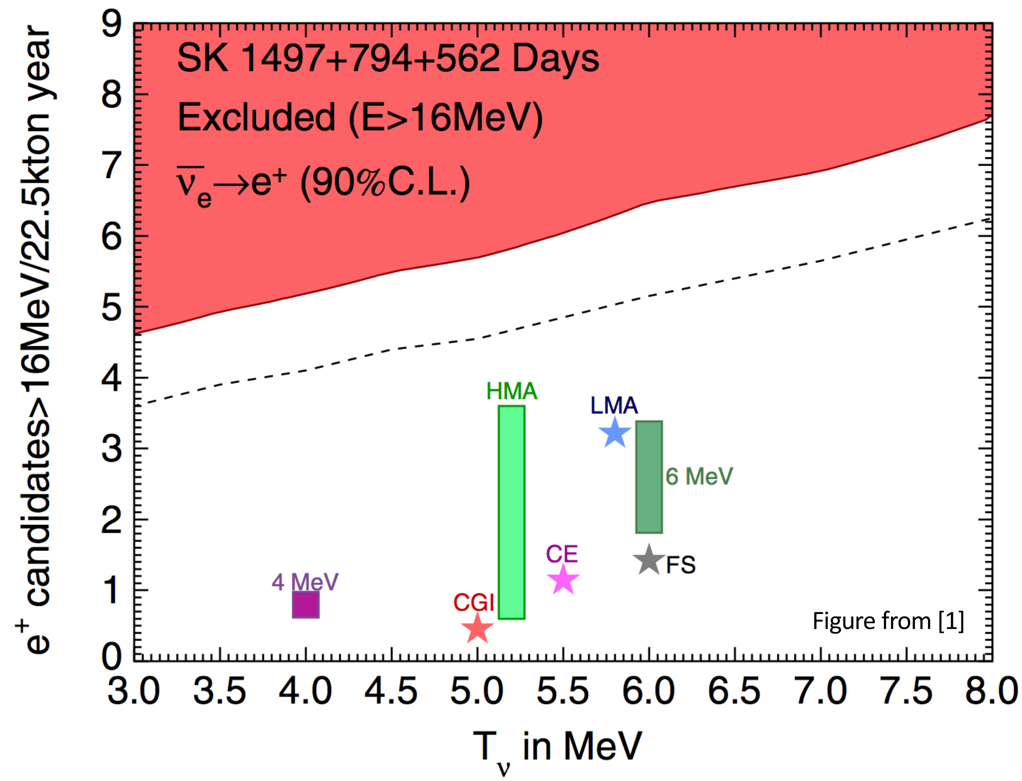
- Invisible-muon decays (higher energy)
- NC elastic scattering (lower energy)





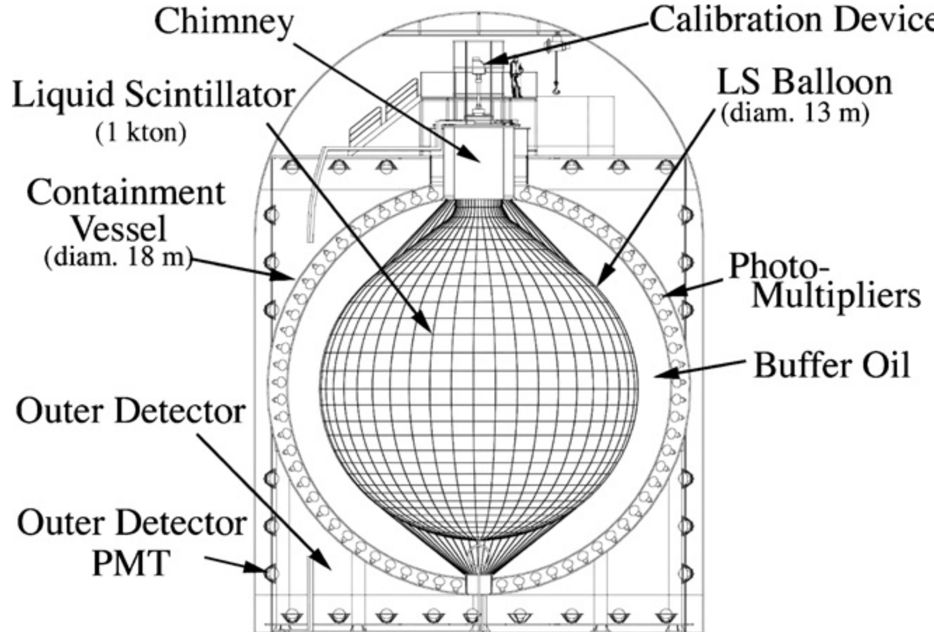
Super-Kamiokande

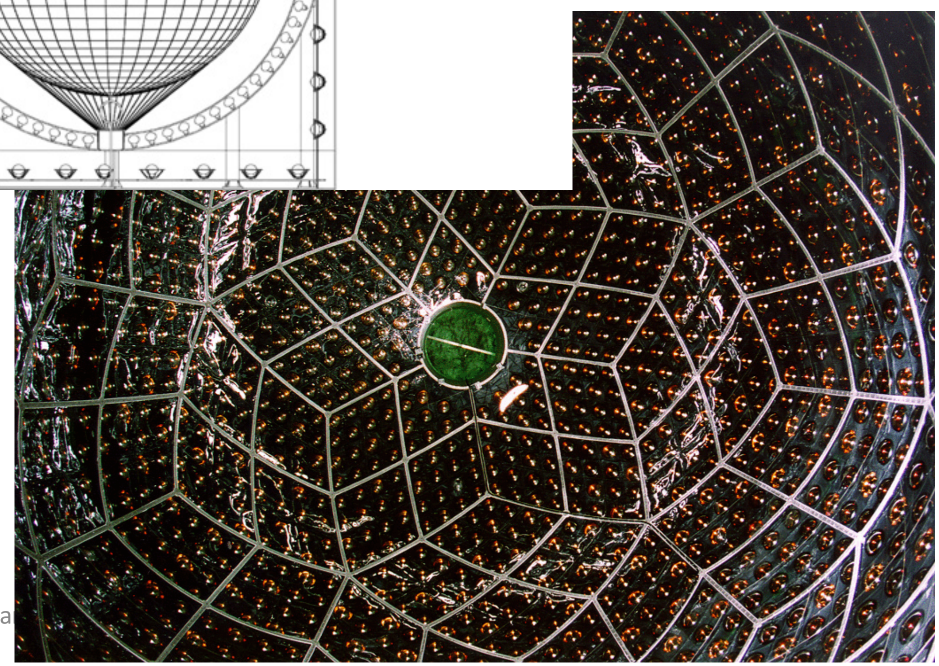




KamLAND

1kt liquid scintillator detector also in Kamioka mine. Running from 2002-11, searches for the DSNB through delayed coincidence.





Backgrounds:
- Spallation with positron and neutron in f.s.
- NC interactions with nuclei

KamLAND

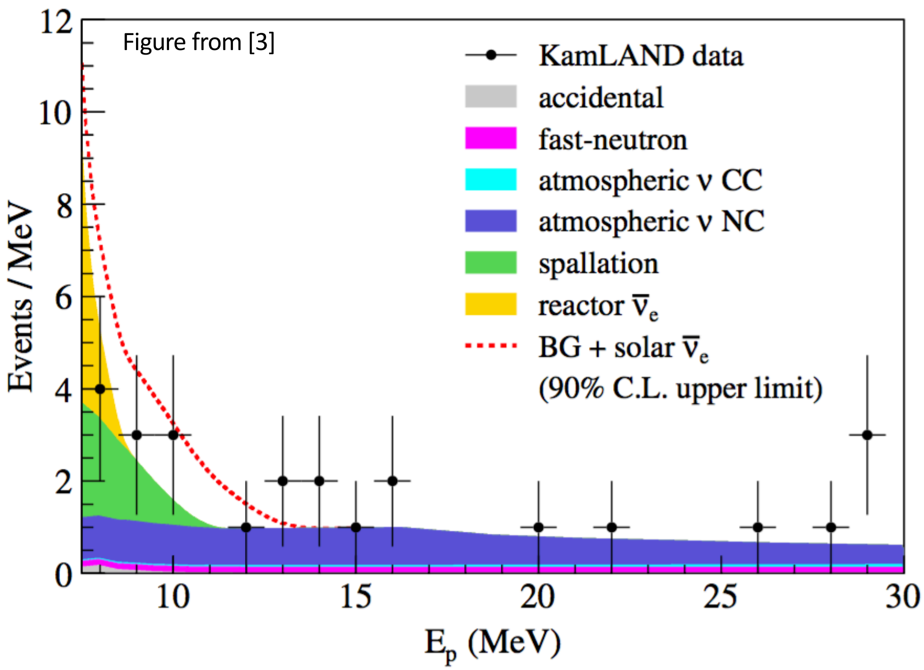


Figure from [3]
KamLAND data
accidental
fast-neutron
atmospheric ν CC
atmospheric ν NC
spallation
reactor $\bar{\nu}_e$
BG + solar $\bar{\nu}_e$
(90% C.L. upper limit)
Events / MeV
E_p (MeV)

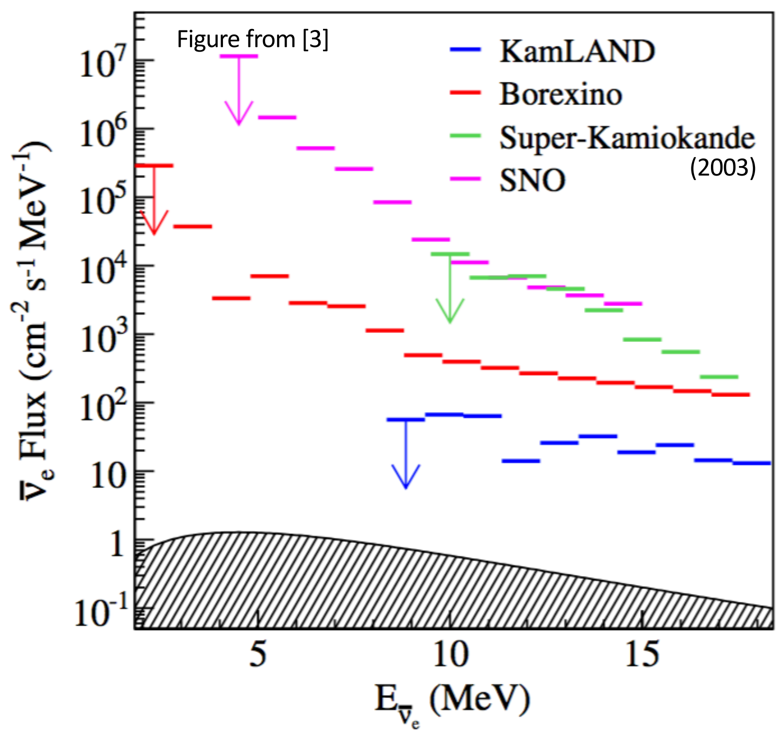
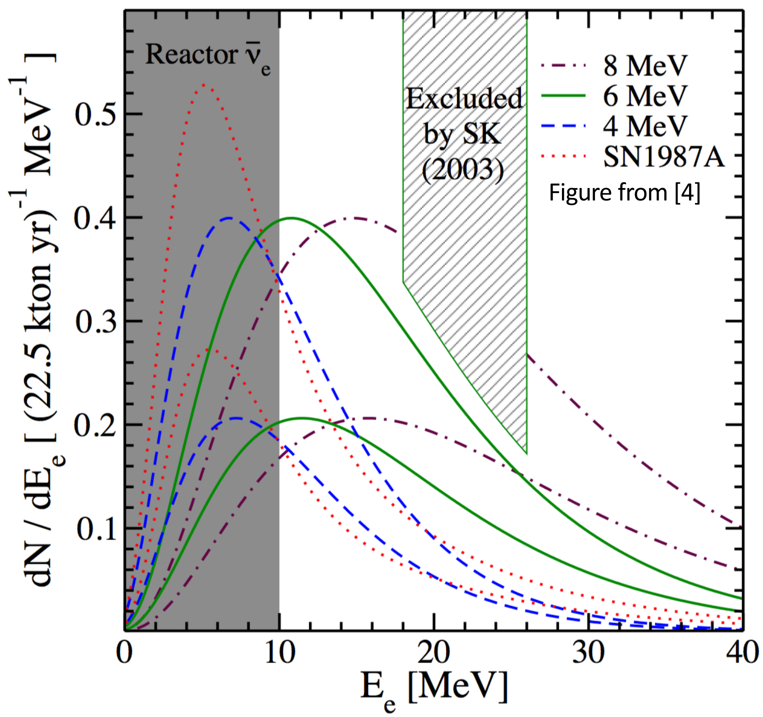


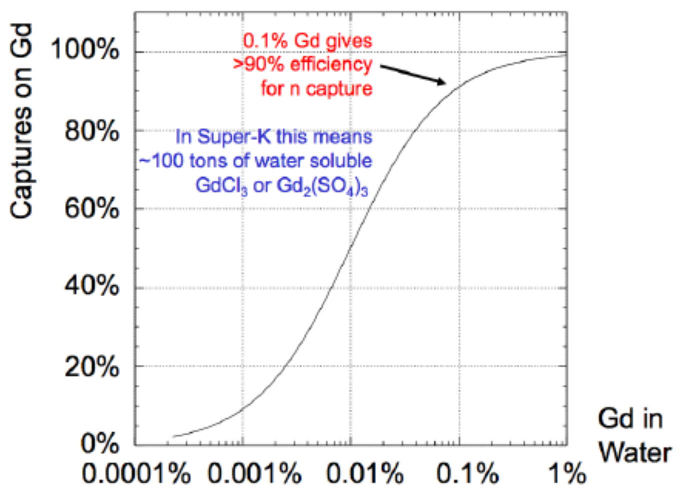
Figure from [3]
KamLAND
Borexino
Super-Kamiokande
(2003)
SNO
$\bar{\nu}_e$ Flux (cm^{-2} s^{-1} MeV^{-1})
$E_{\bar{\nu}_e}$ (MeV)

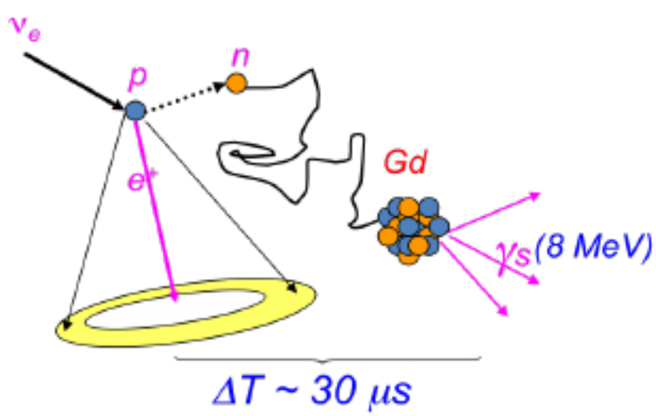
But can we do better..?

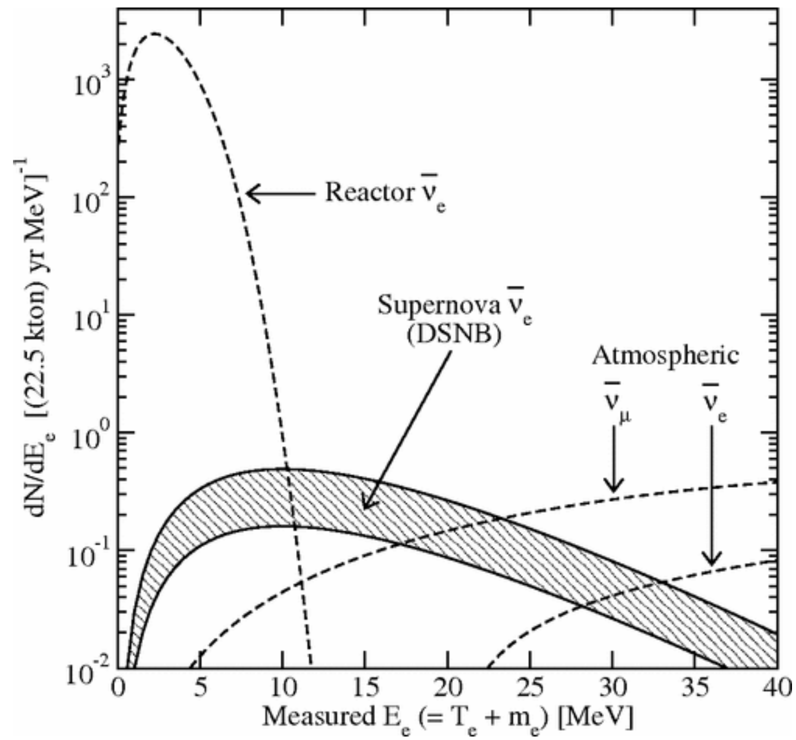
Of course! Super-Kamiokande has an inverse beta decay efficiency of only 13%.



GADZOOKS! (Gadolinium Antineutrino Detector Zealously Outperforming Old Kamiokande, Super!)







J. F. Beacom and M. R. Vagins, “Antineutrino Spectroscopy with Large Water Cerenkov Detectors,” *Phys. Rev. Lett.*, vol. 93, no. 17, p. 171101, Oct. 2004.

Figures: P. Fernandez, “Status of GADZOOKS!: Neutron Tagging in Super-Kamiokande,” in *Nuclear Physics B Proceedings Supplement 00* (2014), pp. 1–8.

Others (more distant future)

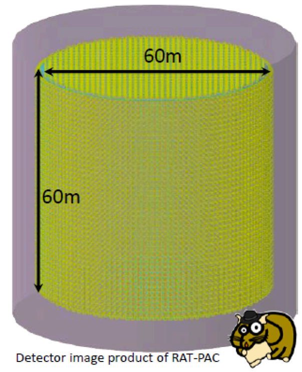
Liquid argon detector (DUNE):

DEEP UNDERGROUND
NEUTRINO EXPERIMENT
www.dunescience.org

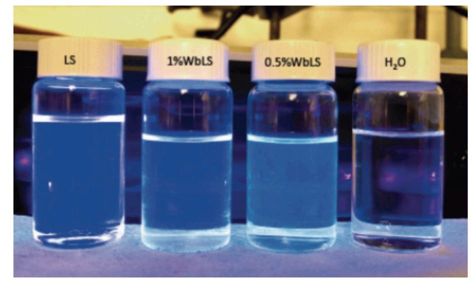
$$\nu_e + {}^{40}\mathrm{Ar} \rightarrow e^- + {}^{40}\mathrm{K}^*$$

$$\bar{\nu}_e + {}^{40}\mathrm{Ar} \rightarrow e^+ + {}^{40}\mathrm{Cl}^*$$

Water-based liquid scintillator (ASDC/THEIA):

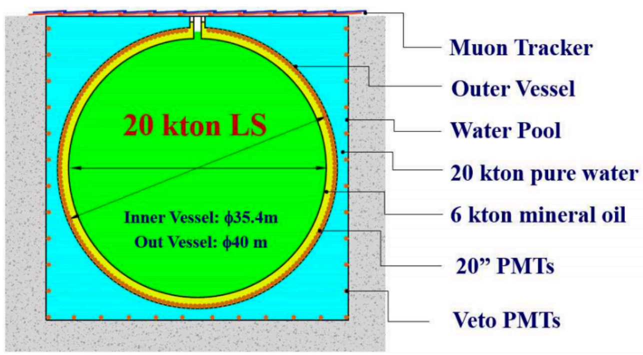


arxiv:1504.08284

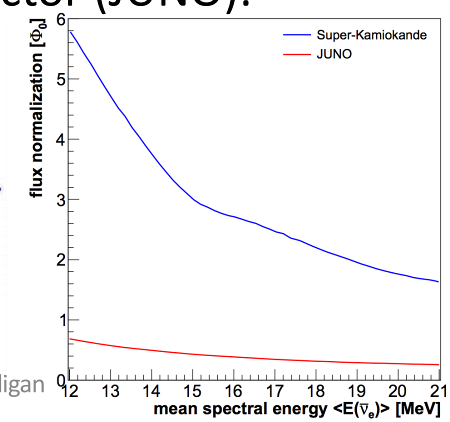


arxiv:1409.5864

Large liquid scintillator detector (JUNO):



arxiv:1507.05613



Last thoughts

- Supernova neutrinos are useful to both astrophysics and neutrino physics.
- The DSNB gives neutrino experiments something to strive for while also preparing for the next near-by supernova.
- In recent history, we have been able to get close to observing the DSNB (likely within a factor of <10).
- The DSNB is observable in the near future!

References

[1] K. Bays *et al.*, "Supernova relic neutrino search at Super-Kamiokande," *Physical Review D*, vol. 85, no. 5, Mar. 2012.

[2] H. Zhang *et al.*, "Supernova Relic Neutrino search with neutron tagging at Super-Kamiokande-IV," *Astroparticle Physics*, vol. 60, pp. 41–46, Jan. 2015.

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[4] S. Horiuchi, J. F. Beacom, and E. Dwek, "Diffuse supernova neutrino background is detectable in Super-Kamiokande," *Phys. Rev. D*, vol. 79, no. 8, p. 083013, Apr. 2009.

+ others where cited.